Ion America

Co-production of hydrogen and electricity from an SOFC generator

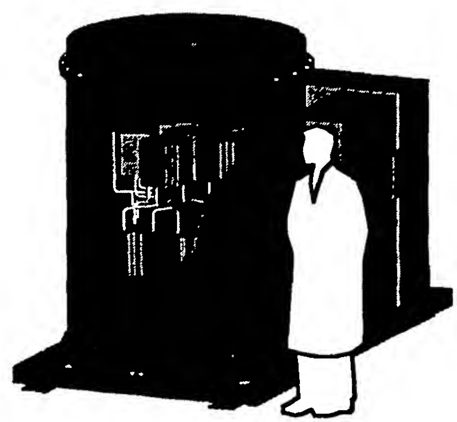
April 2003

Can hydrogen and electricity be co-produced economically?

Ion America's 100 kWe SOFC generator

Fuel
- natural gas
- biogas
- logistic fuels

Air



Reliable electric power

High quality heat (co-generation)

Hydrogen

Distributed generation model – point of use production eliminates the cost of T&D

Hydrogen for Transportation

Factors

- Lack of hydrogen infrastructure makes refueling fuel cell vehicles (FCV's) difficult.
- Distribution from centralized plants not economical.

Hydrogen Production

- Water electrolysis is clean (if renewable sources used), but too expensive.
- Decentralized reforming plants for H_2 may be economical.

Many potential users will have requirements for both hydrogen and electricity

  - industrial complexes
  - product distribution warehouses
  - multi-unit housing

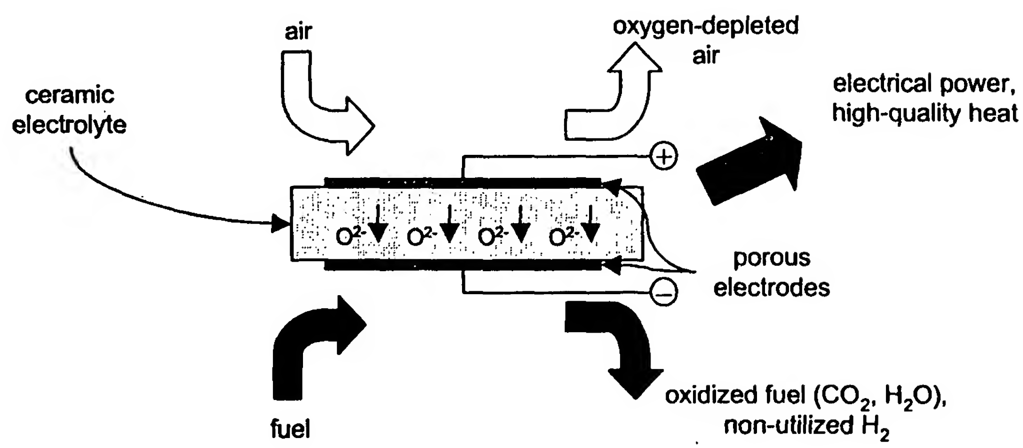
SOFC Hydrogen and Electricity Generation

Solid oxide fuel cells (SOFC) produce hydrogen during electrical power generation.

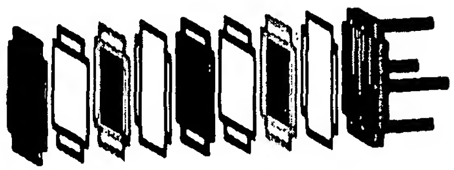
Within a SOFC stack, we have

steam methane reforming:	$CH_4 + H_2O \rightarrow CO + 3H_2$
water-gas shift:	$CO + H_2O \rightarrow CO_2 + H_2$
CO oxidation:	$CO + {}^1/_2O_2 \rightarrow CO_2$ + electricity + heat
hydrogen oxidation:	$H_2 + {}^1/_2O_2 \rightarrow H_2O$ + electricity + heat
partial oxidation:	$CH_4 + {}^1/_2O_2 \rightarrow CO + 2H_2$ + electricity + heat

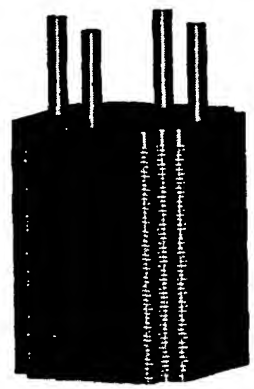
Not all hydrogen produced is utilized for power generation (utilization can be varied from 50% – 80%).



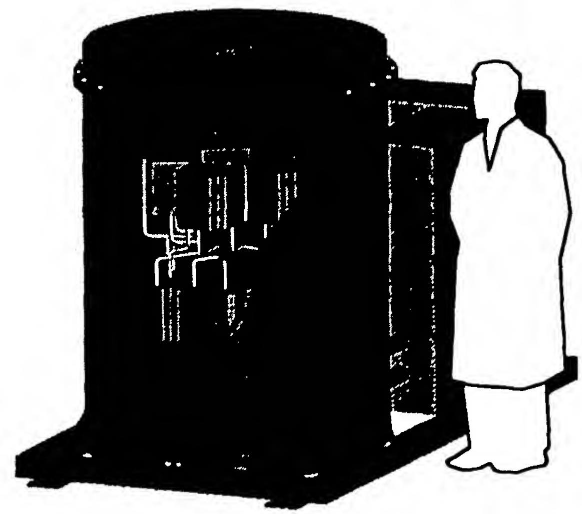
Ion America's SOFC Product



Fuel cells are stacked together with separator plates (interconnects) and seals to attain the required power output.



A 10 kW modular SOFC stack.



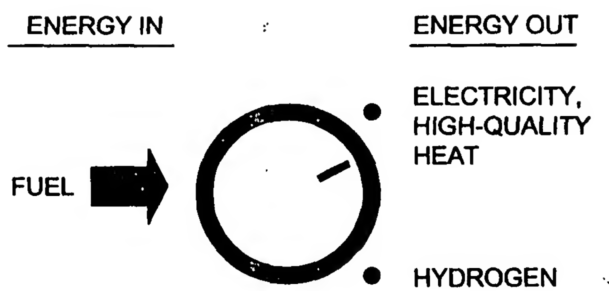
100 kW SOFC-HDHP modular system. Has 10 SOFC stacks.

Easily configured for other sizes.

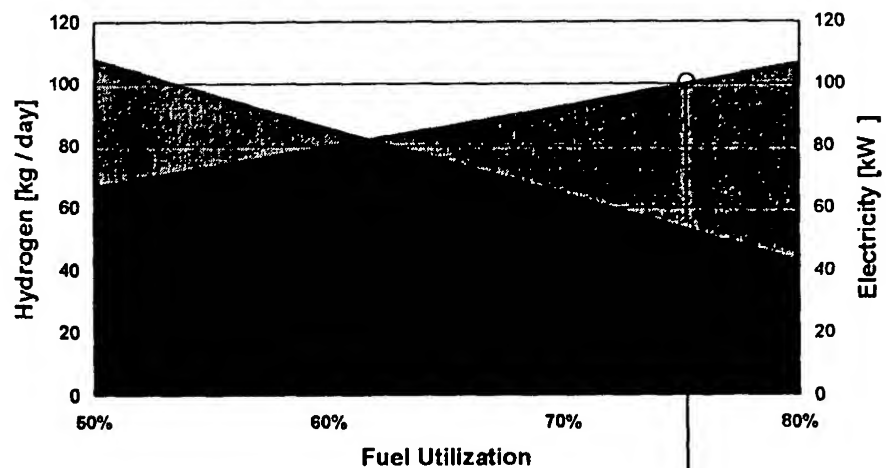
Modular design for increased reliability.

Hydrogen and Electricity Availability

Rate of electricity and hydrogen production as a function of fuel (methane) utilization, total fuel flow held constant.



Electricity and hydrogen co-production at constant fuel flow



Example: 100 kWe SOFC generator at 75% fuel utilization

A hydrogen production rate of **50 kg / day** corresponds to

- a gasoline energy equivalent of 47 gallons / day (equal energy basis)
- support for a fleet of 80 fuel cell vehicles

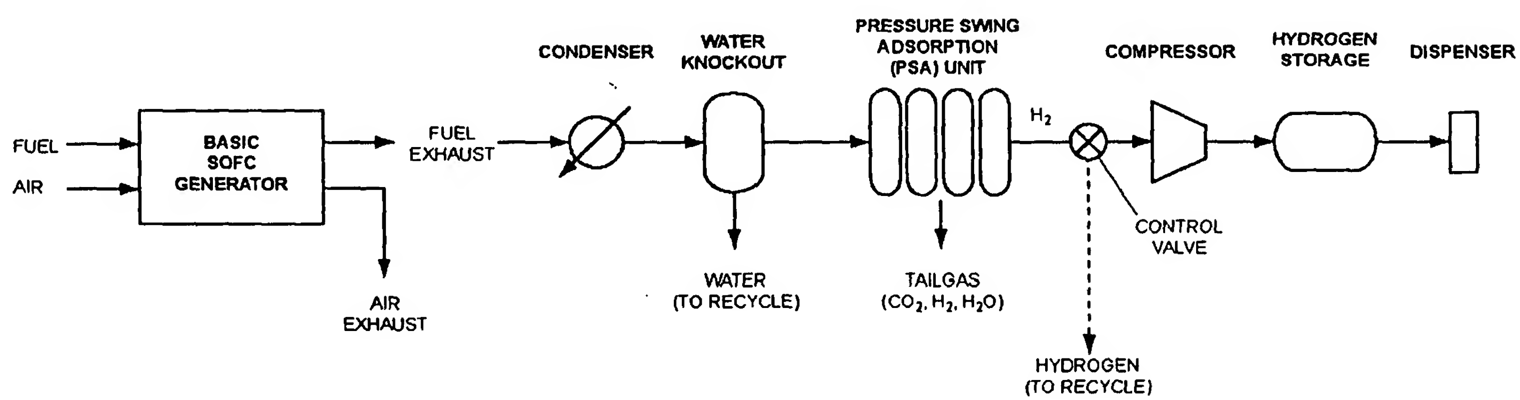
Cost of Production

Approach

- Start with Ion America's basic 100 kWe generator and cost of electricity calculation
  - No gas recycle
  - No co-generation
- Add detailed model for hydrogen processing in order to produce a **7000 psi** product
  - Equipment selection, sizes, and costs estimated from Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002.

Simplified Flow Diagram

- The basic SOFC generator is cost-modeled elsewhere.
- Hydrogen storage at 7000 psi is sized for one day's worth of production.
- Other hydrogen separation and compression components sized for maximum production capacity.
- Fuel utilization controlled at the generator.



Two Scenarios

For both scenarios, the SOFC plant generates a constant 100 kWe.

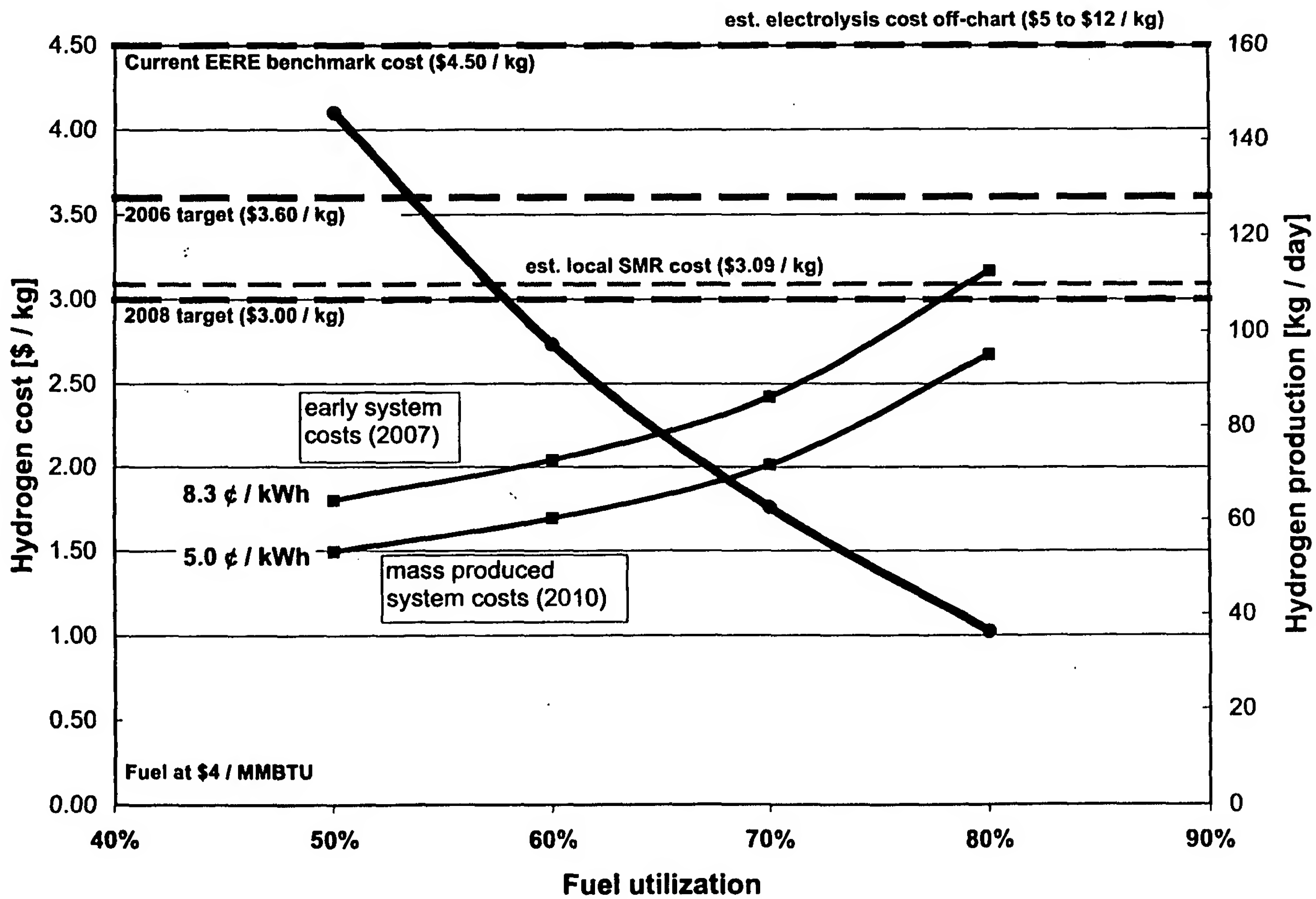
Case 1 (2007)

- Early Ion America SOFC product at $1,400 / kW capital equipment.
- Natural gas fuel at $4 / MMBTU
- High O&M costs
  - $0.01 / kWh for SOFC
  - 20% of compressor cost
  - 5% of balance of separation system cost

Case 2 (2010)

- Mass-produced Ion America SOFC product at $400 / kW capital equipment
- Natural gas fuel at $4 / MMBtu
- Reduced O&M costs
  - $0.005 / kWh for SOFC
  - 10% of compressor cost
  - 2% of balance of separation system cost

Hydrogen Production Metrics per 100 kW Electricity Generated



Sample Calculation and Assumptions

"Case 1" point at 60% utilization

SOFC Electricity Generation

	Ion America SOFC system
SOFC Assumptions	
Capital Costs [$/kW]	1,400
Heat Rate [Btu/kWh]	8,530
O&M Cost [$/kWh]	0.01
Amortization Period [y]	8.3
Capacity Factor [%]	90%
Energy Production Costs in ¢ / kWh	
Cost of capital	1.8
Depreciation	2.1
Fuel Cost	3.4
O&M Cost	1.0
Electricity Cost [¢/kWh]	8.3

Basic Assumptions	
Fuel cost [$/MMBTU]	4.00
Cost of capital	10%
SOFC conversion efficiency	40%

SOFC H2 Production

		Ion America H2 system
H2 Production Assumptions		
Base Equipment		88,801
Mfr Markup	15%	13,320
Miscellaneous	10%	8,880
Total capital equipment		111,001
Equipment life [y]		10
Capacity [kg H2/y]		29,158
H2 Productions Costs in $ / y		
Depreciation	straight	11,100
Cost of capital		11,100
Compressor O&M	20%	4,000
Other O&M	5%	3,440
Process gas (SOFC effluent)		14,741
Electricity (from SOFC generator)		15,000
Total annual cost [$/y]		59,382
Hydrogen cost ($ per kg)		2.04
Gasoline equiv. cost ($ per gal)		2.16

Supporting calculations for H2 production

Additional Capital Equipment (2003)	
15,000 kg/y basis	
Unit	Cost
Water removal	1,200
PSA	14,000
Compressor	20,000
Storage	34,601
Dispenser	18,000
Assembly	1,000
Total	88,801
compressor electricity calculation	
cost basis of 3 HP for 300 SCFH	
SOFC electricity [$/kWh]	0.083
annual cost [$/y]	12,812
allowance for electricity usage over compression	10%
days of operation	300
size of generator [kW]	100
nominal fuel utilization	60%
LHV of fuel [Btu/lb]	21,518
H2 separation yield	90%
production rate [kg/d]	97

Comparison to Steam Methane Reforming and Electrolysis

At about **$2.00 / kg**, the estimated cost of **SOFC-produced hydrogen** is well under the costs using other approaches.

- Hydrogen produced by local **steam methane reforming** is estimated to cost **$3.09 / kg**. [1]

- Estimates for cost of hydrogen produced by **water electrolysis** ranges from 1.5 [2] to 3.6 [3] times the cost of steam methane reforming, or **$5.00 to $12.00 / kg**.

1. Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002. Cost adjusted for natural gas pricing at $4 / MMBTU.
2. Stuart Energy USA, "Filling up with hydrogen 2000," Proceedings of the 2002 U.S. DOE Hydrogen Program Review, 2002 (with electricity at $0.075/kWh).
3. B. Eliasson and U. Bossel, ABB Switzerland white paper, January 2003.

Conclusion

- Large consumer base will exist for generation of electricity and hydrogen at point-of-use.
- Hydrogen production can be added at relatively low capital cost to Ion America's SOFC generators.
- Ion America's SOFC-based approach is cost-effective and will have market entry by 2007.

Co-production of hydrogen and electricity from an SOFC generator

Ion America

April 2003

Hydrogen for transportation

Factors

- Lack of hydrogen infrastructure makes refueling fuel cell vehicles (FCV's) difficult.
- Existing natural gas pipelines from centralized plants have compatibility, capacity issues.
- Truck transportation from centralized plants not economical.
- Water electrolysis is clean (if renewable sources used), but expensive.

- Studies show that small, decentralized plants based on reforming can be economical.
- Many potential users would have demand for both hydrogen and electricity (fleets, apartment complexes, manufacturers, etc.).

SOFC hydrogen and electricity generation

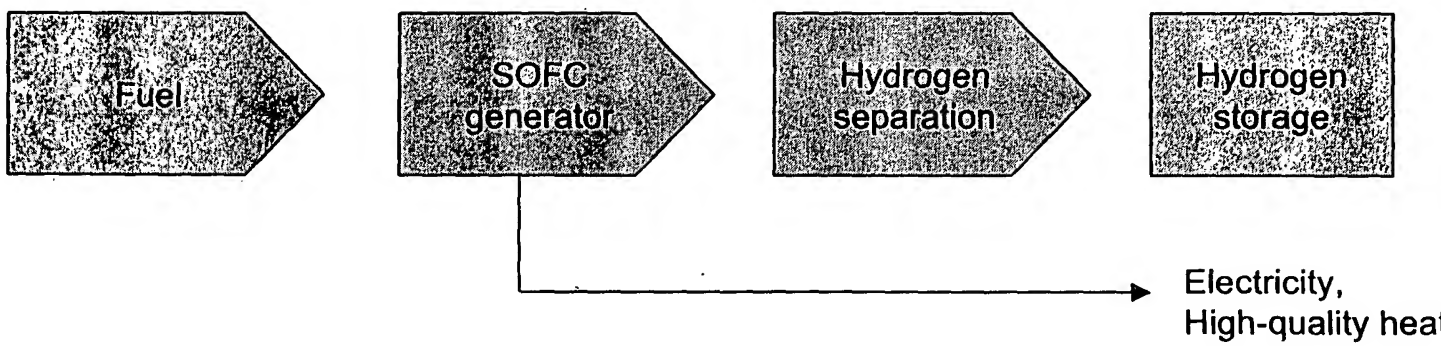
- A solid oxide fuel cell (SOFC) power generator produces hydrogen as a by-product of electricity generation. Any hydrocarbon gas can be used as fuel.
  An SOFC is a power generator and fuel reformer in one package.

- The hydrogen is contained in the stack effluent.
  The hydrogen can be separated and purified at no additional fuel cost.

- The fuel cost only significantly affects the cost of electricity produced, not the hydrogen.

- Can be 100% green if renewable fuel sources (e.g. biogas) are used.

Hydrogen and electricity production by SOFC



- SOFC generators produce hydrogen internally from excess fuel
- Relative amounts of electricity and hydrogen produced are easily controlled by user
- Power generation costs are competitive with centralized generation
- Efficient use of hydrocarbon fuel in SOFC results in low emissions
- Realizes full benefit of distributed generation

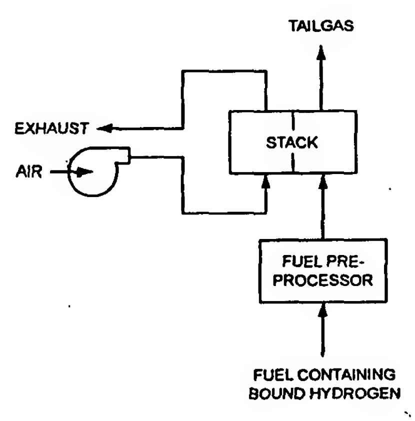
Hydrogen and electricity production by SOFC (continued)

- An Ion America SOFC generation unit operating on hydrocarbon fuel produces hydrogen as a by-product, mixed with other gases and water.
- This hydrogen might be separated from other gases and compressed.

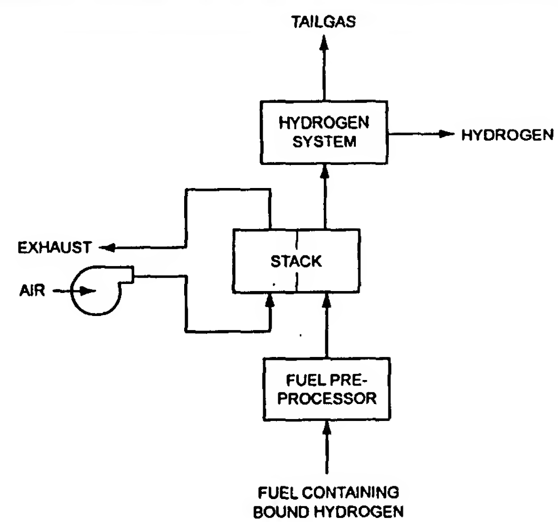
A 100 kWe generator leaves more than 50 kg H_2 per day in the effluent

- This rate will support an 80-vehicle fleet of FCVs at 12,000 miles per year, per vehicle.
- More vehicles can be supported with additional fuel usage.

Simplified flow diagram



BASIC SOFC GENERATOR



SOFC GENERATOR WITH HYDROGEN RECOVERY SYSTEM

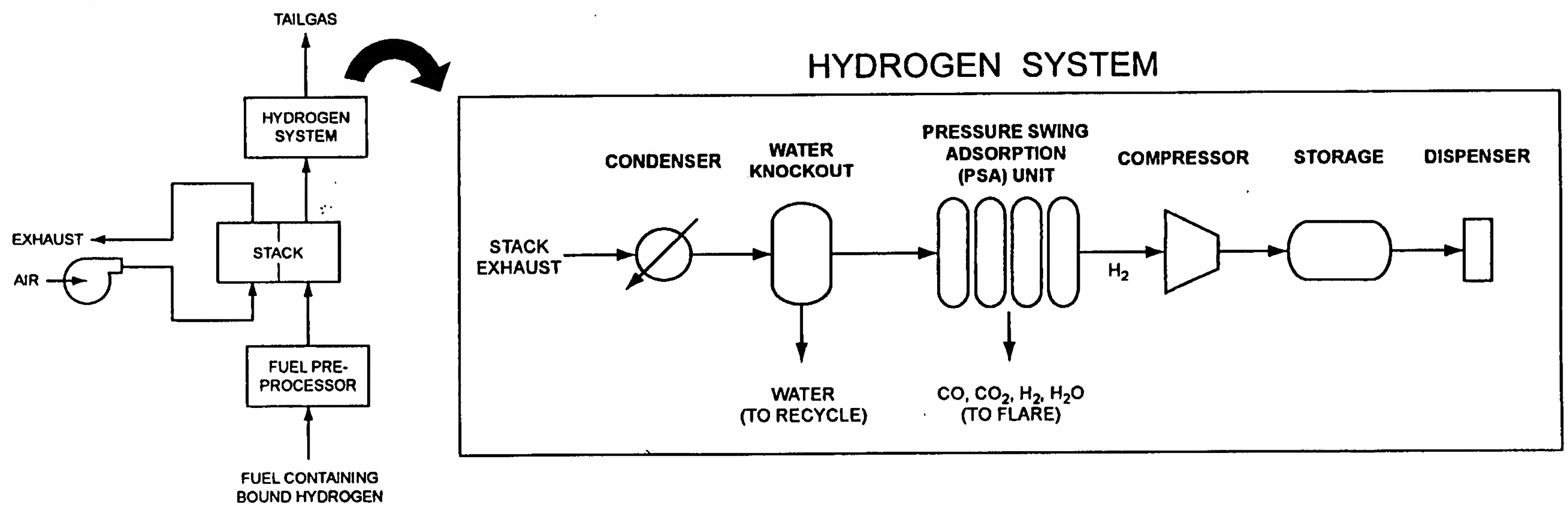
- SOFC generator acts as a power-generating partial oxidation and steam-methane reformer

$$CH_4 + O_2 \rightarrow CO_2 + 2H_2 + \text{electricity} + \text{heat}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 + \text{electricity} + \text{heat}$$

- The tailgas might be used for heating/cooling, recycled, flared etc. OR the hydrogen might be extracted, compressed, and stored for use.

Hydrogen separation, compression, storage and dispensing details



- An SOFC generator already carries many components needed for hydrogen production:
  - reformer (stack)
  - blowers and pumps
  - heat exchangers
  - controllers, valves, other infrastructure
- The additional required capital equipment costs are for separation, compression, storage, and dispensing.
- The required units have been selected, sized, and costed using a detailed 2002 DOE study for decentralized steam-methane reforming stations of similar size (reference 1 on page 11).

Cost of hydrogen

A detailed capital cost model has been developed for the SOFC generator.

Capital costs start at $1,400 / kW in 2006, fall to $400 / kW in 2011 at full production.

Two scenarios considered in following pages:

Gasoline equivalent cost for typical FCV's

"High-cost" case

- SOFC cost of $1,400 / kW
- fuel at $8 / MMBtu (and correspondingly high electricity cost)
- elevated O&M costs

→ $1.03 / gallon

"Low-cost" case

- SOFC cost of $400 / kW
- fuel at $4 / MMBtu
- lower O&M costs

→ $0.82 / gallon

"High cost" scenario

SOFC Electricity Generation

	Ion America SOFC system
SOFC Assumptions	
Capital Costs [$/kW]	1,400
Heat Rate [Btu/kWh]	8,530
O&M Cost [$/kWh]	0.01
Amortization Period [y]	8.3
Capacity Factor [%]	90%
Energy Production Costs in ¢ / kWh	
Cost of capital	1.8
Depreciation	2.1
Fuel Cost	6.8
O&M Cost	1.0
Electricity Cost [¢/kWh]	11.7

Basic Assumptions	
Fuel cost [$/mmBTU]	8.00
Cost of capital	10%
SOFC conversion efficiency	40%

SOFC H2 Production

		Ion America H2 system
H2 Production Assumptions		
Base Equipment		72,000
Mfr Markup	15%	10,800
Miscellaneous	10%	7,200
Total capital equipment		90,000
Equipment life [y]		10
Capacity [kg H2/y], max at 15,000		15,000
H2 Productions Costs in $ / y		
Depreciation	straight	9,000
Cost of capital	10%	9,000
Compressor O&M	10%	2,000
Other O&M	5%	2,600
Process gas (SOFC effluent)		0
Electricity (from SOFC generator)		11,000
Total annual cost [$/y]		33,600
Hydrogen cost ($ per kg)		2.24
Gasoline equiv. cost ($ per gal)		1.03

Supporting calculations for H2 production

Additional Capital Equipment (2003)
15,000 kg/y basis

Unit	Cost
Water removal	1,200
PSA	14,000
Compressor	20,000
Storage	17,800
Dispenser	18,000
Assembly	1,000
Total	72,000

compressor electricity calculation	
cost basis of 3 HP for 300 SCFH	
SOFC electricity [$/kWh]	0.117
annual cost [$/y]	9,292
allowance for electricity usage over compression	10%
days of operation	300
size of generator [kW]	100
nominal fuel utilization	70%
LHV of fuel [Btu/lb]	21,518
H2 separation yield	90%
potential production rate [kg/d]	62

NOTES
- SOFC stack and balance-of-plant have different depreciation periods; 8.3 years is the cost-weighted system average.
- Value of high-quality heat generated by the SOFC system (co-generation) is neglected.
- H2 production assumes completion of steam methane reforming reaction and no water gas shift reaction.
- Capital equipment costs for hydrogen generator are estimated to match a 100 kWe SOFC generator.

"Low cost" scenario

SOFC Electricity Generation

	Ion America SOFC system
SOFC Assumptions	
Capital Costs [$/kW]	400
Heat Rate [Btu/kWh]	8,530
O&M Cost [$/kWh]	0.005
Amortization Period [y]	8.3
Capacity Factor [%]	90%
Energy Production Costs in ¢ / kWh	
Cost of capital	0.5
Depreciation	0.6
Fuel Cost	3.4
O&M Cost	0.5
Electricity Cost [¢/kWh]	5.0

Basic Assumptions	
Fuel cost [$/mmBTU]	4.00
Cost of capital	10%
SOFC conversion efficiency	40%

SOFC H2 Production

		Ion America H2 system
H2 Production Assumptions		
Base Equipment		72,000
Mfr Markup	15%	10,800
Miscellaneous	10%	7,200
Total capital equipment		90,000
Equipment life [y]		10
Capacity [kg H2/y], max at 15,000		14,579
H2 Productions Costs in $ / y		
Depreciation	straight	9,000
Cost of capital	10%	9,000
Compressor O&M	10%	2,000
Other O&M	2%	1,040
Process gas (SOFC effluent)		0
Electricity (from SOFC generator)		5,000
Total annual cost [$/y]		26,040
Hydrogen cost ($ per kg)		**1.79**
Gasoline equiv. cost ($ per gal)		**0.82**

Supporting calculations for H2 production

Additional Capital Equipment (2003)
15,000 kg/y basis

Unit	Cost
Water removal	1,200
PSA	14,000
Compressor	20,000
Storage	17,800
Dispenser	18,000
Assembly	1,000
Total	72,000

compressor electricity calculation	
cost basis of 3 HP for 300 SCFH	
SOFC electricity [$/kWh]	0.050
annual cost [$/y]	3,870
allowance for electricity usage over compression	10%
days of operation	300
size of generator [kW]	100
nominal fuel utilization	75%
LHV of fuel [Btu/lb]	21,518
H2 separation yield	90%
potential production rate [kg/d]	49

NOTES
- *SOFC stack and balance-of-plant have different depreciation periods; 8.3 years is the cost-weighted system average.*
- Value of high-quality heat generated by the SOFC system (co-generation) is neglected.
- H2 production assumes completion of steam methane reforming reaction and no water gas shift reaction.
- Capital equipment costs for hydrogen generator are estimated to match a 100 kWe SOFC generator.

Hydrogen production via steam methane reforming and electrolysis

In comparison to the estimated SOFC hydrogen cost of $1.79 to $2.24/kg ($0.82 to $1.03 / gallon gasoline):

- Hydrogen produced by local steam methane reforming is estimated to cost $3.38/kg [1]
  - gasoline equivalent of $1.55 / gallon

- Estimates for cost of hydrogen produced by water electrolysis ranges from 1.5 [2] to 3.6 [3] times the cost of steam methane reforming
  - gasoline equivalent of $2.40 to $5.58 / gallon

1. Directed Technologies Inc., "Cost and performance comparison of stationary hydrogen fueling appliances," Task 2 Report to U.S. DOE, April 2002.
2. Stuart Energy USA, "Filling up with hydrogen 2000," Proceedings of the 2002 U.S. DOE Hydrogen Program Review, 2002 (with electricity at $0.075/kWh).
3. B. Eliasson and U. Bossel, ABB Switzerland white paper, January 2003.

Hydrogen production via SOFC

- Valuable by-product of low-cost SOFC electricity
- Low additional capital cost
- Hydrogen as cheap as tax-free gasoline
- Large potential market
- No additional infrastructure
- 100% green with renewable fuel

High Density Energy Storage with Solid Oxide Regenerative Fuel Cells

Ion America

Electrical Energy Storage

High density electrical energy storage critical for several military and civilian applications.

Other storage device requirements include

- High efficiency.
- High reliability.
- Long service life.
- Low noise.
- Environmentally compatible – low emissions.
- Low thermal signature.
- Low pressure air-breathing.

Ion America Solid Oxide Regenerative Fuel Cells (SORFC) meet all requirements.

Competing Technologies

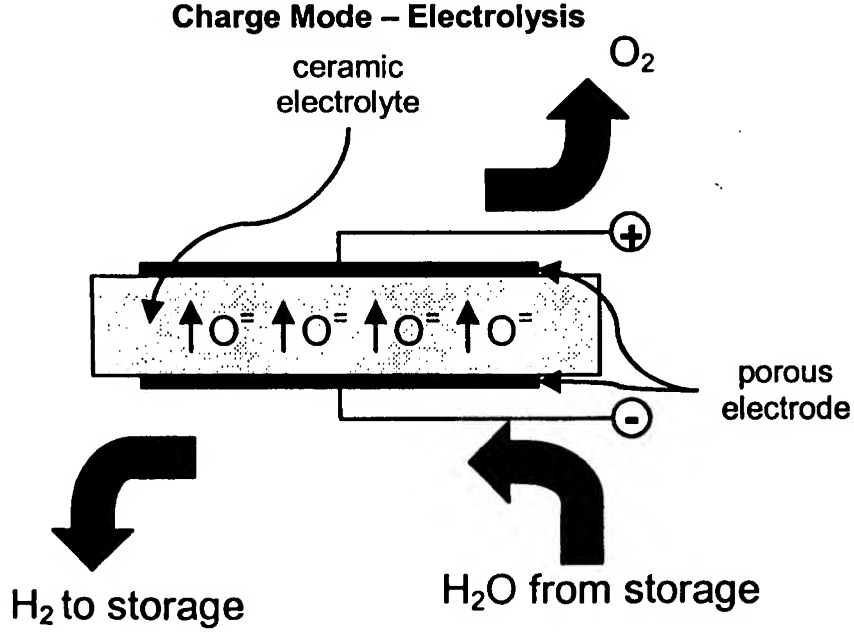
- Rechargeable batteries
  - Low energy density.
- Flywheels
  - Low energy density.
  - Vibration.
  - Gyroscopic effects.
  - Short-term operation.
- Proton Exchange Membrane (PEM) regenerative fuel cells.
  - Require storage of hydrogen *and* oxygen.
  - Difficulty breathing rarefied air.
  - Wetting and freezing issues with electrolyte.
  - Losses by diffusion through electrolyte.
  - Electrolyzer and fuel cell realized with two separate devices.
  - Low round-trip efficiency.

Solid Oxide Regenerative Fuel Cells (SORFC)

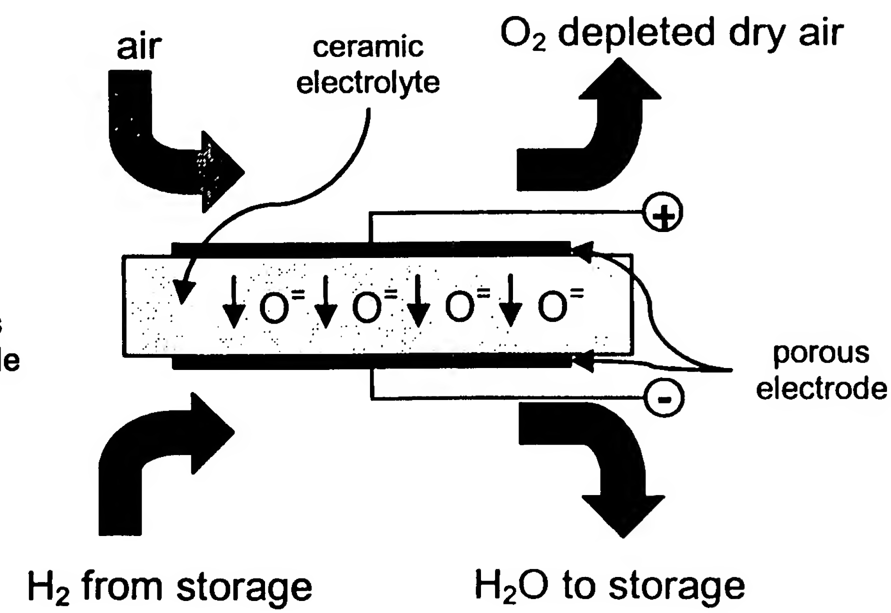
- Based on reversible solid oxide fuel cells.

  In charge mode the SORFC functions as an electrolyzer and regenerates hydrogen (and oxygen) from stored water.
- In discharge mode the SORFC functions as a fuel cell which generates electrical energy from hydrogen and oxygen (can be rarefied air).

Charge Mode – Electrolysis

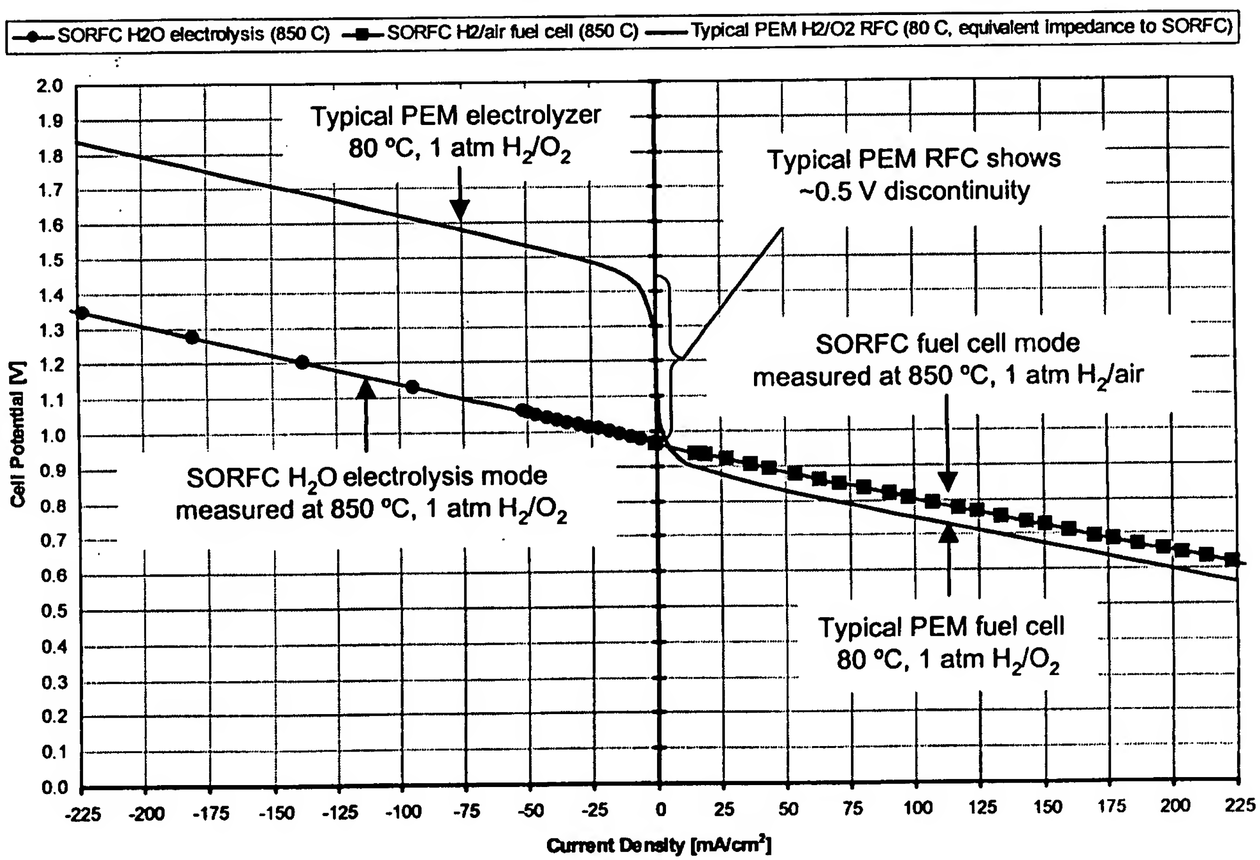


Discharge Mode – Fuel Cell



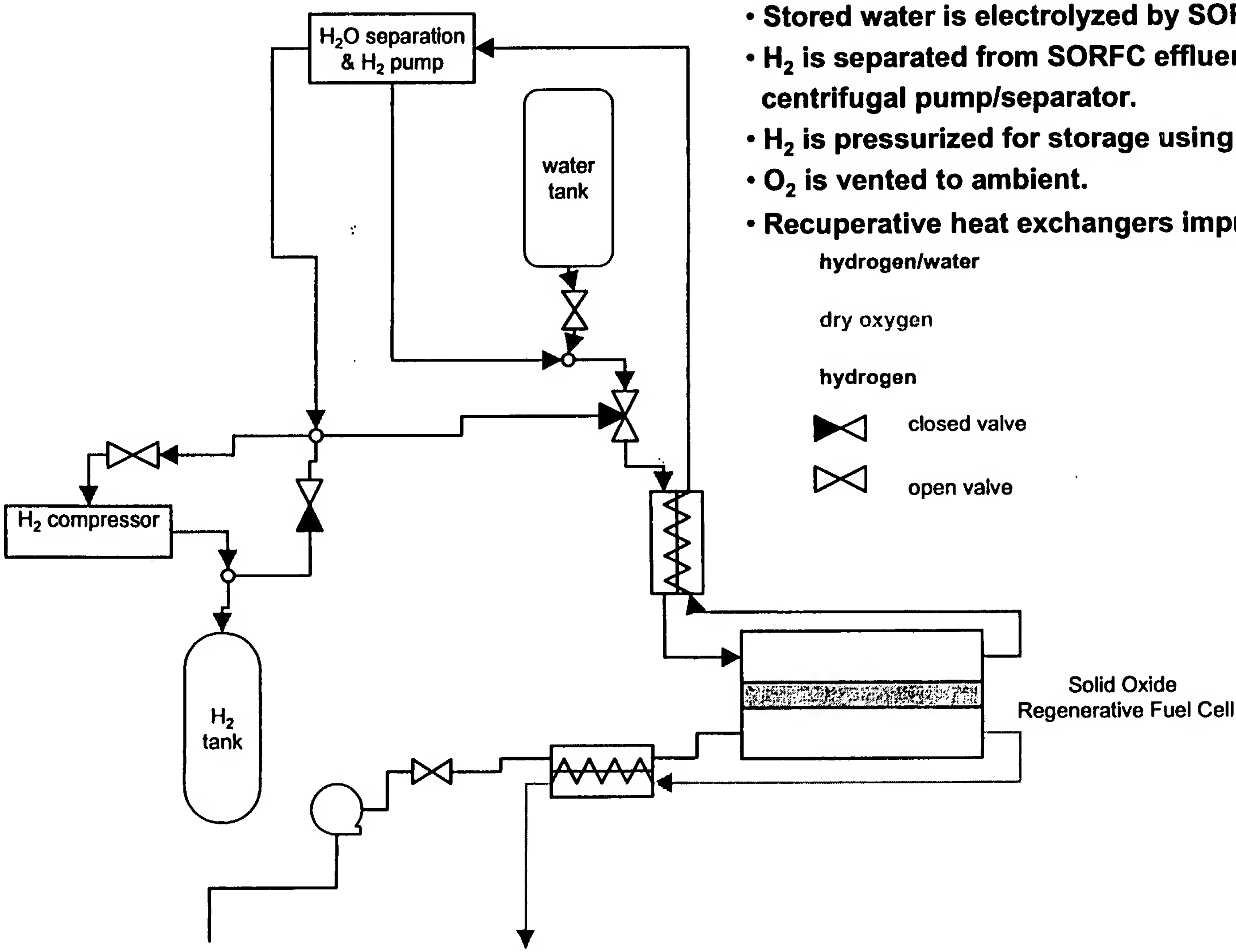
SORFC Compared to PEM RFC

- There is no measurable discontinuity in the SORFC polarization curve.
- Air-breathing SORFCs are not subject to water loss, dryout, or freezing.
- SORFCs can breathe rarified air, resulting in significantly higher specific energy compared to PEM RFCs, especially if reserves are carried.



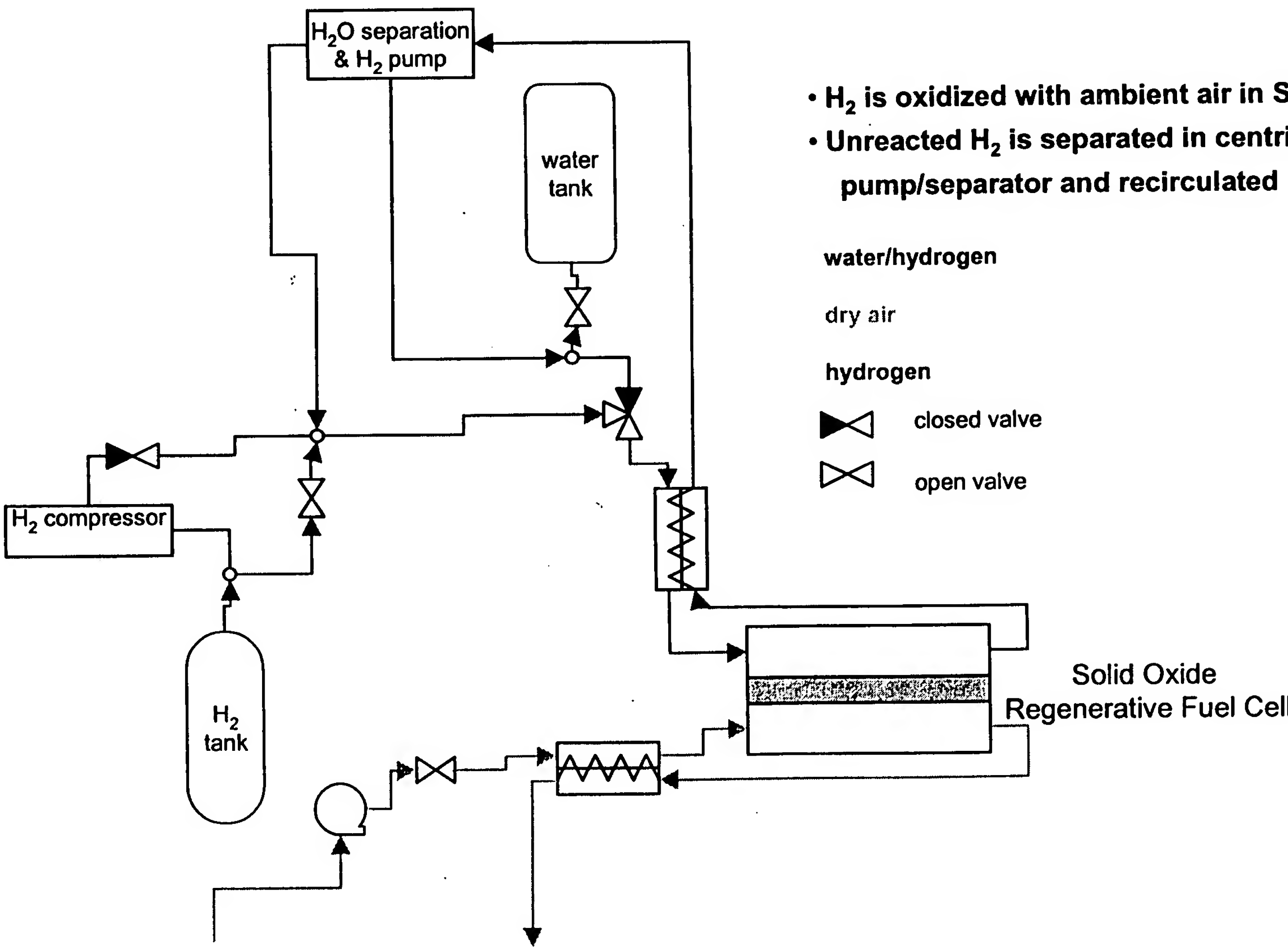
SORFC in Charge Mode

- Stored water is electrolyzed by SORFC.
- H_2 is separated from SORFC effluent with centrifugal pump/separator.
- H_2 is pressurized for storage using electrochemical devic .
- O_2 is vented to ambient.
- Recuperative heat exchangers improve system efficiency



SORFC in Discharge Mode

- H_2 is oxidized with ambient air in SORFC.
- Unreacted H_2 is separated in centrifugal pump/separator and recirculated into SORFC.



Applications

Continuous electrical power for remote locations utilizing solar panels and regenerative solid oxide fuel cells.

Allows storage of energy at low cost periods, and consumer generation of power during high-cost periods.

- Can be combined effectively with other renewable energy sources (wind, etc.).
- High altitude airplane and airship regenerative electrical power supply.

Remote power for base stations.

- High energy density electrical energy storage for autonomous sites (communication/research/military).

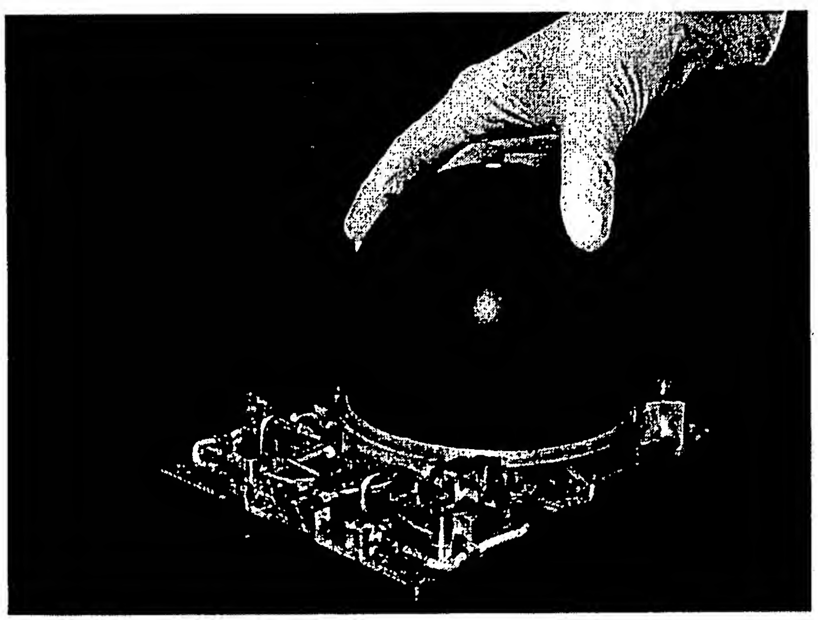
Ion America Expertise in Electrochemical Devices

- Fuel Cells for Space Flight Power.
- PEM technology for Navy applications.

  PEM technology for regenerative power systems for high altitude aircraft.
- Solid Oxide Regenerative Fuel Cells.
- Solid Oxide Electrolyzers.
- Solid Oxide Fuel Cells.
- Commercial Solid Oxide Fuel Cell systems from 10kW to 100kW.

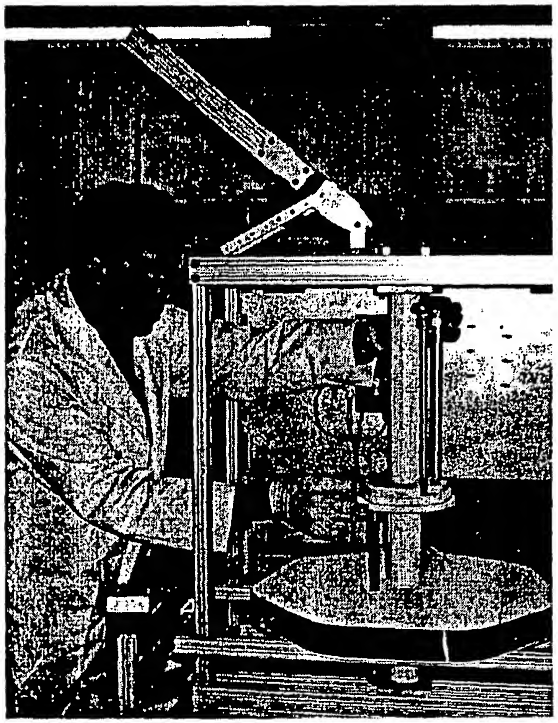
Ion America – High Reliability Heritage

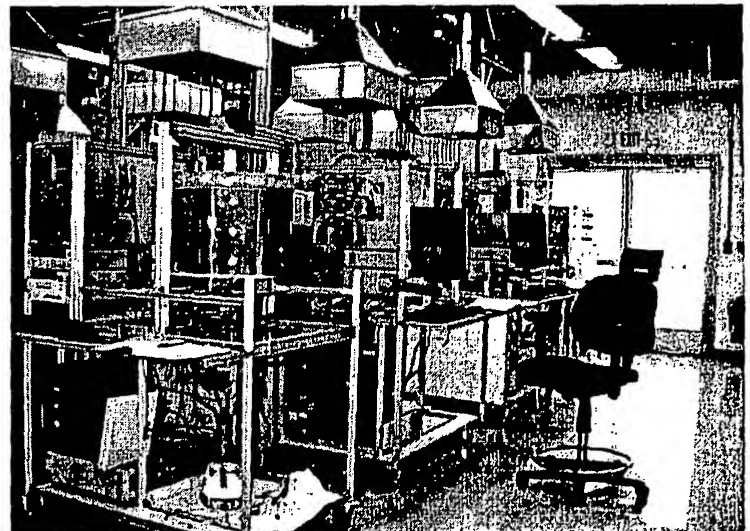
- PEM electrolyzers for submarines.
- Fuel cell systems for space flight.
- Solid oxide electrolyzers for Mars exploration.
- Solid oxide electrolyzers for Air Force high altitude aircraft.
- Solid oxide electrolyzers for battlefield oxygen supply.



Space flight qualified Oxygen Generator System (OGS) for the 2001 Mars Lander

Technical Status





- Cells operated for >2000 hours.
- Three-cell stack operated for >1000 hours, thermally cycled eleven times.
- Five-cell stacks currently in operation.

Intellectual Property

- Ion America presently has 17 patents in the pipeline for
  - interconnect designs
  - electrode formulations
  - electrolyte designs
  - seals
  - stacks
  - systems and applications